Hot-Spot Fatigue and Impact Damage Detection on a Helicopter Tailboom

P. X. QING[1], H. WILSON[2], A. G. BAINES[2], N. BORDICK[3], S. BANERJEE[1], H. CHUNG[1], S. BEARD[1] and M. PAPPAKOSTAS[1]

ABSTRACT

Monitoring the health of aircraft components and identifying problems before they can affect airworthiness has been a long-term goal in aviation. Current maintenance procedures are performed on a conservative, calendar or usage-based schedule rather than condition-based. These scheduled maintenance practices are time-consuming, labor-intensive and expensive. Furthermore, as structures age, maintenance service frequency (often unscheduled) and costs increase while performance and availability decrease. A promising solution to these issues is the application and integration of Condition Based Maintenance (CBM) and Structural Health Monitoring (SHM) technologies and processes.

To enable more efficient and effective airframe maintenance, fatigue cracking and impact damage detection technologies were developed and demonstrated on a commercial tailboom. This paper discusses the application of SMART Layer technology to detect damage caused by cyclic loads and ballistic impact on the tailboom. The damage locations and sizes were compared with the computed values from the SHM system.

INTRODUCTION

There are many challenges to implementing a flight-ready SHM system for rotorcraft. The functionality and reliability of the SHM system needs to remain consistently accurate under variable flight conditions, such as changes in loading and thermal cycling during operation. Many rotorcraft components incorporate complex geometries and varying material compositions, making reliable damage detection even more challenging. This paper provides validation of Acellent's SHM system in successfully monitoring fatigue cracks initiated from cyclical loading conditions; detecting, locating and quantifying ballistic damage; and monitoring for ballistic impacts in the tailboom area. The program concluded with the successful

[1]Peter X. Qing, Sourav Banerjee, Howard Chung, Shawn Beard, Mark Pappakostas, Acellent Technologies, Inc., Sunnyvale, CA.
[2]Henry Wilson, Andrew Baines, Bell Helicopters Textron Inc., Ft. Worth, TX
[3]Nathaniel Bordick, Aviation Applied Technology Directorate, Ft. Eustis, VA

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
SEP 2011	**N/A**	**-**

4. TITLE AND SUBTITLE
Hot-Spot Fatigue and Impact Damage Detection on a Helicopter Tailboom

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Acellent Technologies, Inc., Sunnyvale, CA.

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADA580921. International Workshop on Structural Health Monitoring: From Condition-based Maintenance to Autonomous Structures. Held in Stanford, California on September 13-15, 2011 . U.S. Government or Federal Purpose Rights License.

14. ABSTRACT
Monitoring the health of aircraft components and identifying problems before they can affect airworthiness has been a long-term goal in aviation. Current maintenance procedures are performed on a conservative, calendar or usage-based schedule rather than condition-based. These scheduled maintenance practices are time-consuming, labor-intensive and expensive. Furthermore, as structures age, maintenance service frequency (often unscheduled) and costs increase while performance and availability decrease. A promising solution to these issues is the application and integration of Condition Based Maintenance (CBM) and Structural Health Monitoring (SHM) technologies and processes. To enable more efficient and effective airframe maintenance, fatigue cracking and impact damage detection technologies were developed and demonstrated on a commercial tailboom. This paper discusses the application of SMART Layer technology to detect damage caused by cyclic loads and ballistic impact on the tailboom. The damage locations and sizes were compared with the computed values from the SHM system.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

demonstration of the integration of the impact monitoring system with the damage detection system. Damage detection was triggered upon impact event detection, utilizing the same SMART Layer® Sensor Network in this dual monitoring scenario.

Acellent was selected by Bell Helicopter to demonstrate the SHM technology in support of the structures section of the Operations Support and Sustainment Technologies (OSST) Program sponsored by the Aviation Applied Technology Directorate (AATD) of the Army. One of the goals of this program was to validate technology that can be used as directed by the Department of Defense Logistics Transformation Strategy [1] in support of the Army Aviation CBM Plus Plan [2] for transitioning the current regimented and unscheduled maintenance burden to a CBM protocol facilitating cost savings for aircraft maintenance and providing operational benefits, such as greater mission readiness and maximum inspection efficiency.

SHM SYSTEM DESCRIPTION

Recent advances in sensor technology, material processing, damage modeling, and system integration enables new developments in structural evaluation and inspection technologies to overcome the existing shortcomings of the traditional inspection protocol. Among them is the concept of SHM, which uses a built-in structural diagnostic system. Sensor networks are permanently mounted on structures that then provide the capability to monitor the condition of the structures throughout their service life. A built-in monitoring system consists of three major components: 1) Built-in sensor network, 2) Integrated hardware, and 3) Intelligent diagnostic software.

Built-in Sensor Network

The SMART Layer® technology, a thin dielectric film with an array of durable, networked piezoelectric sensors, monitors the integrity of the composite and metal structures. The SMART Layer is well-established in the field of SHM and is well-known for its unique ability to provide wide structural coverage for gathering data. The SMART Layer's networked sensors fully eliminate the need for each sensor to be installed individually.

Integrated Hardware

SMART Suitcase™ systems address specific structural health monitoring needs:

(1) ScanSentry: an energy-efficient, battery-operated controller for actively sensing the integrity of local structural areas, such as hot-spots, or components where low power and portability are needed.

(2) ScanGenie: a robust system that controls the active interrogation of both metal and composite structures through sensor activation and response for damage detection, particularly for large area monitoring.

(3) IMGenie: a lightweight, energy saving, battery-powered device. The system uses a passive mode to detect impact events in real-time. The system reports the location, time and force or energy of the impact.

Intelligent Diagnostic Software

Diagnostic software is the foundation of an SHM system. Acellent developed a Smart Patch System (SPS) for monitoring "Hot-spots" in rotorcrafts [3] and aircrafts. The developed system is both suitable for on-board and off-board applications. In this program, the SPS was utilized for fatigue crack monitoring in validation of its functionality [4]. In addition to the sensing capability, the SPS is equipped with an early alarm system and calibration procedures for detecting damage size precisely.

A modified version of the Acellent Impact Monitoring (AIM) software was implemented to allow ballistic impact detection to trigger damage detection. This software, PMS-AIM, is classified as a hybrid Active-Passive SHM system. The system was developed based on the principle of using the passive mode as a self-trigger mechanism to scan the structure (Figure 1). The passive mode process determines the impact location on the structure and estimates the impact magnitude. The damage location is confirmed and the size of damage is determined by the active mode process.

For the ballistic testing, the SmartComposite is used in the active mode process. SmartComposite interrogates the structure, using Lamb waves to detect the damage location and size caused from ballistic impact events.

The integration of a distributed sensor network, portable data acquisition hardware, and intelligent SHM software provides the capability of collecting, storing, and analyzing information related to the structure's integrity (Figure 2). The system can scan the structure and analyze the resulting data during normal operations. Diagnostic results can be evaluated in real-time by the operator, to ensure mission success and platform survivability. This type of system can substantially reduce the time and expense required to evaluate the structural condition and reduce life-cycle costs. Such an SHM technology is not simply meant to detect structural failure, but also to provide an early indication of physical damage [5]. The early warning provided by an SHM system can then be used to define remedial strategies before the structural damage leads to catastrophic failure.

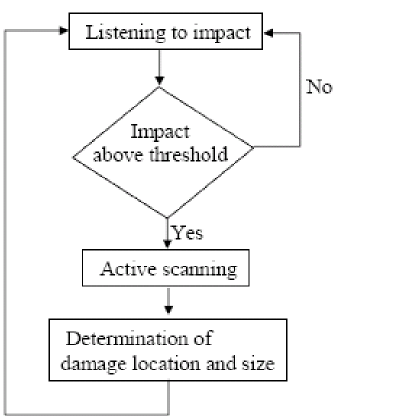


Figure 1: Passive-active System Flow for Damage Detection

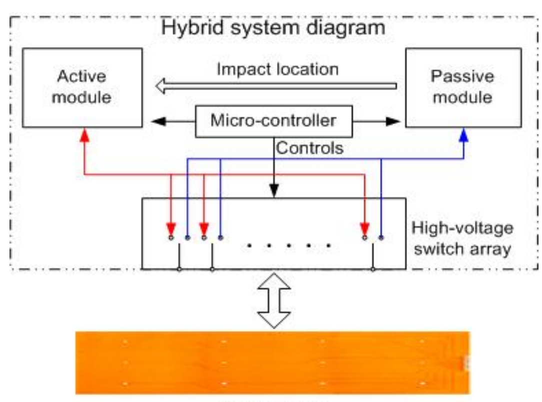


Figure 2: A Hybrid System using both Passive and Active Modules for SHM

TAILBOOM FATIGUE CRACK DETECTION

Setup

A section of a helicopter tailboom structure was used for the fatigue test. This study aimed to validate the SMART Layer sensing technology in the application of damage detection for the tailboom under cyclic loadings. The ScanSentry hardware and SmartPatch software were utilized to demonstrate the damage detection process in fatigue testing. The setup is shown in Figure 3.

In the study, two hot-spot monitoring areas were defined at the joint of the horizontal stabilizer on the tailboom structure, as shown in Figure 4.

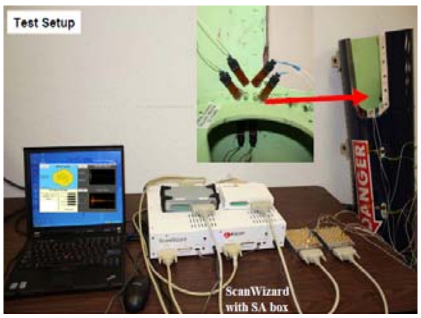


Figure 3: The Test Setup for Fatigue Test

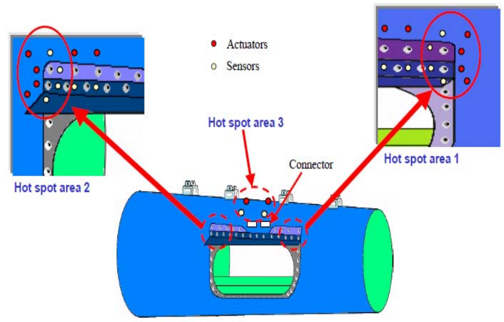


Figure 4: Hot-spot Areas in Tailboom for Fatigue Crack Monitoring

There were a total of 28 PZT disks that were mounted on the tailboom for testing: 14 of them were used as actuators, while the other 14 PZT disks were used as sensors. Among the 28 PZT disks, 16 PZT disks were placed in the two fatigue hot-spot areas to detect cracks initiated from the 4 rivets determined by Bell Helicopter; 8 PZT disks were placed around another 4 rivets to detect any possible cracks initiated from these rivets; the other 4 PZT disks were placed over a large area. Each of the PZTs had a diameter of 1/8” and thickness of 10 mils. The test was conducted in the Mechanical Systems Test Laboratory of Bell Helicopter Textron, Inc., Fort Worth, Texas.

Result

Automatic data collection control in the SmartPatch software was used for collecting data during the fatigue testing. The interval setup for fatigue testing was 2 hours. The test lasted for 31 hours when a crack formed and propagated through ½ the circumference of the tailboom.

After installing the sensors at the designated hot-spots, baseline data from the structures undamaged state was collected. A total of 10 baseline datasets were collected under various conditions, e.g. at zero load, at maximum and intermediate load towards right, at maximum and intermediate loads towards left etc. Data was automatically collected every two hours during the test using automated SmartPatch software. The datasets that were collected every two hours were first filtered through an environmental compensation algorithm, referencing baseline datasets that were initially collected. For individual wave paths, damage indices were calculated using

the signal features contained in the frequency domain. Then the damage index was calculated for the overall hotspots.

At the beginning of the test, the damage index for hotspot 1 was growing and suddenly dropped, then followed a wobbling trend. It was identified that the cause for this variation in these datasets was the continuous loading on the structure. The loading condition tends to settle the fixtures and that caused a rise in the damage index. Hence, another one full day of data sets were included in the baseline and environmental compensation was performed accordingly. Afterwards the damage index was wobbling within the noise floor as identified during the test (Figure 5) and the crack was identified when the damage index crossed the threshold of the noise floor. After detection, the crack started to propagate and the crack size steadily increased. Based on the prior study and the in-situ ultrasonic NDE test results, a calibration curve was generated to quantify the crack size. The crack size reported is also shown in Figure 5.

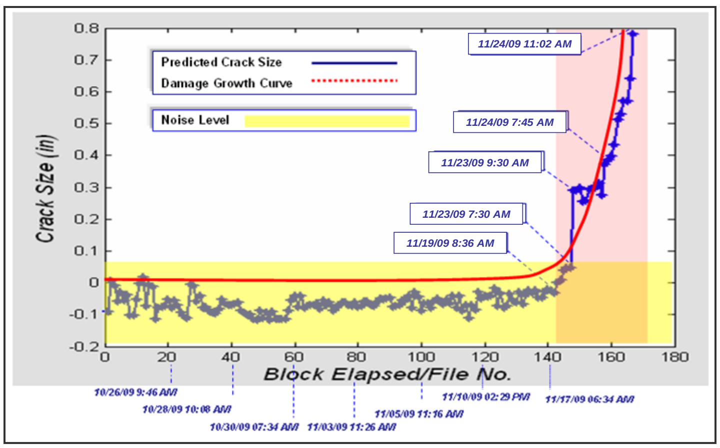


Figure 5: Test Results from Fatigue Crack Monitoring

BALLISTIC IMPACT DETECTION

Setup

A commercial tailboom, shown in Figure 6, was utilized to evaluate the detection capability of the SHM systems. The tailboom was 150 inches long comprised of simple aluminum sheet metal skin/frame structure with an aluminum tail rotor support casting on the aft end. The skin thicknesses were basic .040 inch upper skin and .050 inch lower skin with doublers attached in local areas. The frame thicknesses ranged from .032 inches to .040 inches. The forward end of the tailboom included tailboom-to-fuselage attachments, which were used to restrain it in the test fixture. The aft end of the tailboom included a tail rotor support, which was used as a load application mechanism. There was no horizontal elevator or vertical fin installed on the tailboom.

To monitor impact damage, Acellent utilized a SMART Layer with 28 PZT sensors, each having a diameter of 1/8″ and thickness of 10 mil, elements mounted on the outside surface of the skin, as shown in Figure 7(a)-(b). An additional 8 PZT single sensor elements were mounted on the inside frame of the tailboom as shown in Figure 7(c) to monitor ballistic impact damage on it. The 28 PZT elements monitored approximately a 3 ft long area with an average diameter of 12 inches.

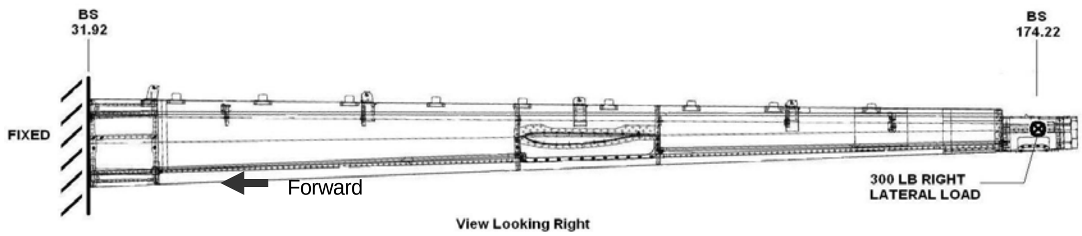
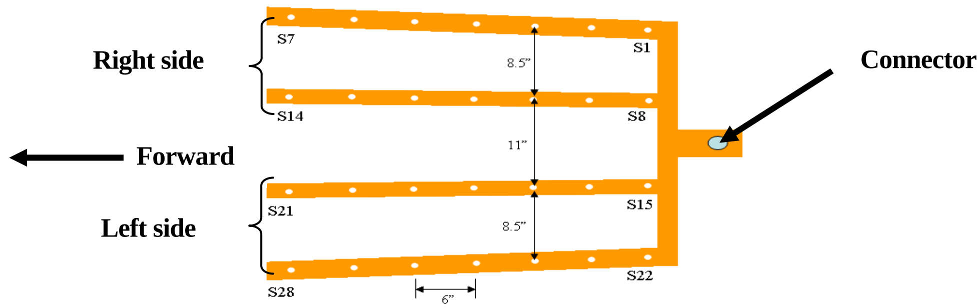


Figure 6: Tailboom for ballistic impact test



(a) SMART Layer mounted on the outside surface of skin

(b) SMART Layer installation on outside surface

(c) Single SMART Layer sensors on inside frame

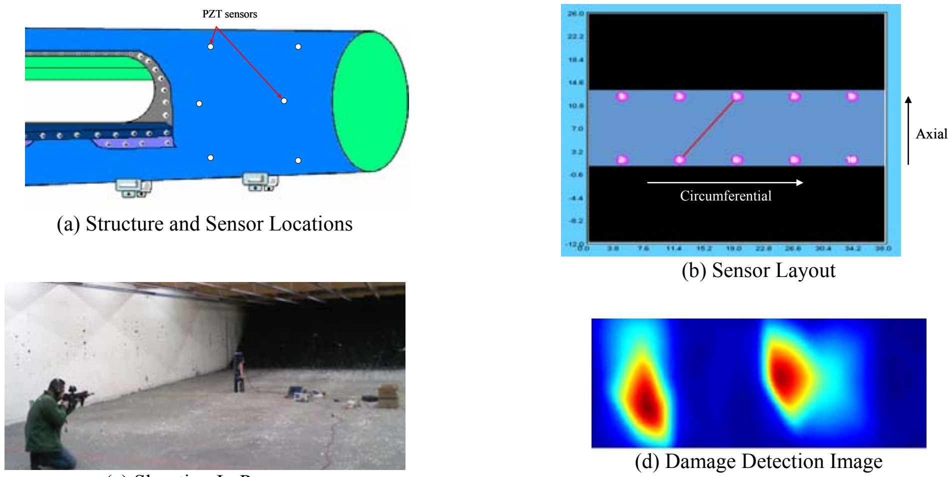
Figure 7: SMART Layers on the Tailboom Skin and Inside Frame

Shooting Range Test for System Calibration: Before deploying the ballistic detection system, Acellent worked out the calibration tests at the shooting range to verify the functionality and the sensitivity of the hardware used for impact monitoring. Ten PZT sensors were used to mount on the surface of the tailboom skin. The test was conducted at a shooting range in the city of Santa Clara, CA, as shown in Figure 8.

The IMGenie was setup for continuous ballistic energy level impact monitoring. Ballistic Test Setup: Figure 9 shows the setup for the ballistic test. The tailboom structure was cantilevered off of a test fixture. At the other end of the fixture, the tailboom was connected with a loading platform using a steel frame. The load platform was used to apply a transverse load to the aft end of the tailboom during the ballistic testing.

Result

The Structural Ballistic Demonstration was conducted on April 20, 2010 at the AATD Ballistic Test Range for Aircraft Component Survivability (BTRACS), located in Fort Eustis, VA.



(a) Structure and Sensor Locations

(b) Sensor Layout

(c) Shooting In Process

(d) Damage Detection Image

Figure 8: Shooting Range Test Result

A total of seven separate shots were conducted on the statically loaded tailboom utilizing two distinct projectiles. The load in the tailboom represented a 1-G hover condition. The projectiles used during this evaluation were the 5.56 x 45 mm M995 AP (Armor Piercing) and the 7.62 x 51 mm M993 AP.

At each shot, the data collection process was triggered by the passive sensing mode using the IMGenie. The PMS-AIM software detected the ballistic impact and started collection of sensor signal data. Figure 10 shows an example of a damage image presentation from the SmartComposite software for detection of the first shot in the ballistic test. SmartComposite also calculated the damage size caused by each shot based on the PZT actuator-and-sensor network geometry using a first arrival time window (FATW) method.

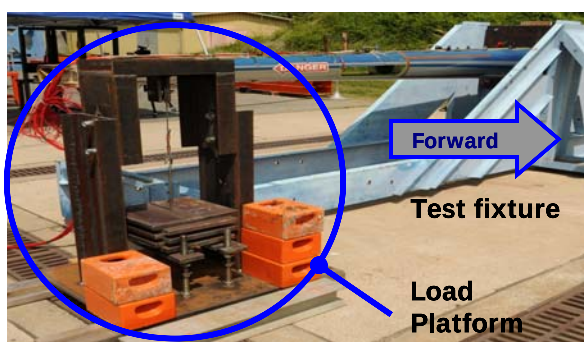


Figure 9: Ballistic Test Setup in Fort Eustis, VA

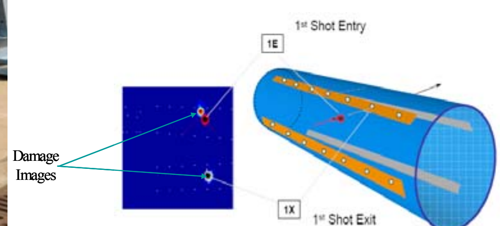


Figure 10: Ballistic Test Result from Damage Detection Imaging

SUMMARY

Acellent was selected by Bell Helicopter to demonstrate SHM technology in support of the structures section of the Operations Support and Sustainment Technologies (OSST) Program sponsored by the Aviation Applied Technology Directorate (AATD) of the Army. Fatigue cracking and impact damage detection technologies were developed and demonstrated on a Bell commercial tailboom. The work under the program has demonstrated the following:

- Acellent's fatigue crack monitoring system based on ScanSentry and SmartPatch software was successful in determining the location and quantifying the size upon calibration.
- Acellent's Impact monitoring system based on IMGenie hardware and AIM software was successful in accurately determining a ballistic impact event and providing the location of the impact event on the structure.
- Acellent's large area monitoring system based on ScanGenie hardware and SmartComposite software was successful in determining the location and quantifying the size of the damage without need for calibration.
- The combination of Acellent's Impact Monitoring system and large area monitoring system was successful in sharing the same SMART Layer to allow an impact event to trigger damage detection, and accurately determine the damage location and size.
- Acellent's SMART Layer was proven to be reliable for fatigue crack monitoring for cyclical loading on the Bell commercial tailboom.
- Combining all 3 of Acellent's SHM technologies would serve as an early warning system to provide some of the much-needed diagnostic information as the foundation of the Army's CBM plus requirements.

Future work includes flight-readying Acellent's hardware, so that a higher TRL rating can be achieved leading to airworthiness certification. Acellent's complete system approach makes it possible for an onboard SHM system flight-tests to be conducted in the future.

ACKNOWLEDGEMENT

This research was partially funded by the Government under Agreement No. W911W6-07-2-0003. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation thereon. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Aviation Applied Technology Directorate or the U.S. Government.

REFERENCES

1. Logistics Transformation Strategy, Department of Defense, Vol. 10, December, 2004.
2. Army Aviation Condition Based Maintenance Plus (CBM+) Plan, Headquarters, Department of the Army, 29 Nov. 2004.
3. Banerjee, S., Qing, X. P., Beard, S., and Chang, F. K., "Rotorcraft's Hot-spot Monitoring using Distributed Smart Patch System," *Proceeding of the 5th European Workshop on Structural Health Monitoring*, 2010.
4. Banerjee, S., Qing, X. P., Beard, S., and Chang, F. K., Prediction of Progressive Damage State at Hot-spot using Statistical Estimation, *Journal of Intelligent Material Systems and Structures, Feb, 2010.*
5. Beard, S., Liu, B.. Qing, P., and Zhang, D., "Challenges in Implementation of SHM," *Proc. of the 7th Int. Workshop on SHM: SHM 2007 Quantification, Validation, and Implementation*, Sept. 2007, Stanford University. Chang F-K (ed). DEStech Publications, Inc.: Lancaster, PA, 2007; 65-84. 2007.